GEARTECH Report No. 2070

Overview of AGMA/AWEA 6006 Standard for Design and Specification of Gearboxes for Wind Turbines

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INTRODUCTION

The AGMA/AWEA Wind Turbine Committee first met in 1991. Its latest document: AGMA/AWEA 6006-AXX, *Standard for Design and Specification of Gearboxes for Wind Turbines* [1], is currently being reviewed by the committee, and is expected to be published in 2003. AGMA/AWEA 6006 reflects latest knowledge about wind turbine gearboxes and offers guidelines for defining loads, specifying all components of gearboxes, auditing manufacturing and quality assurance, operation, and maintenance.

OBJECTIVE

This report provides an overview of AGMA/AWEA 6006, beginning with the origin of the Wind Turbine Committee, and ending with the December 31, 2002 status of the standard. This report is a “getting started” manual for people who are new to gearbox procurement. It provides guidance to purchasers, gear manufacturers and auditors. It explains the background for the guidelines of AGMA/AWEA 6006, and provides links to other publications that assist in understanding AGMA/AWEA 6006 guidelines.

HISTORY

GEARTECH began investigating wind turbine gearbox failures in 1983. Thousands of wind turbines were installed in California during the 1980’s when tax incentives made wind power attractive to investors. Early projects were poorly planned, and off-the-shelf gearboxes were hastily installed in wind turbines. Early wind turbines were based on Danish experience where the wind regime is relatively benign. Little was known about the California winds and operating environment, but it quickly became apparent that conditions in California were much more severe than in Denmark. The result was widespread gearbox failures. While there were many contributing causes of gearbox failures, the lack of knowledge of California wind regimes was a major contributor.

Gearbox failures occurred at wind power sites in the Altamont Pass near Livermore, California, Tehachapi near Bakersfield, California, and in the San Gorgonio Pass in Palm Springs, California. GEARTECH found the environmental conditions at all the sites to be punishing for wind turbines. Palm Springs was the most abusive, Tehachapi less so, and the Altamont Pass the least abusive. Gearboxes failed at all three sites and thousands failed in the Altamont Pass although this was the most benign site. Some gearboxes were more reliable than others, but none seemed immune to failure. During the 1980’s and 1990’s, GEARTECH inspected hundreds of failed wind turbine gearboxes, conducted failure analyses, and wrote failure analysis reports.

The Flender repair facility in Bakersfield, California was overloaded with failed gearboxes from all three California sites. They repaired not only Flender gearboxes, but also a variety of foreign and domestic gearboxes. Wind farm operators were desperate to replace failed gearboxes, and many new repair facilities were born to meet the demand. However, many of the repaired gearboxes operated only a short time before

failing again. It was clear that the gearboxes had to be redesigned to survive in California wind farms.

On September 23, 1991, during the American Wind Energy Association (AWEA) Windpower Conference in Palm Springs, California, the following people met to discuss gearbox failures:

- Robert Errichello, GEARTECH
- Brian McNiff, McNiff Light Industries
- Jane Muller, GEARTECH
- Walt Musial, NREL
- Brent Reardon, MSA

At this ad hoc meeting, it was decided the participant's collective experience should be documented. Therefore, the ad hoc committee members decided to attend the AWEA Standards Coordinating Committee being held at the same AWEA Windpower Conference, and propose a new project to develop guidelines for wind turbine gearboxes.

At the AWEA committee meeting on September 24, 1991, the AWEA committee agreed the guidelines were a worthy project, but suggested the American Gear Manufacturers Association (AGMA) should be involved.

In October 1991, Robert Errichello asked Jim Bentley, then Vice President of the AGMA Technical Division, if an AGMA committee could be formed in cooperation with AWEA. Jim felt such a cooperation was possible and agreed to propose the idea to the AGMA Board of Directors. Approval was subsequently received and the first meeting of the AGMA/AWEA Wind Turbine Committee convened on October 19, 1992. Brent Reardon was elected chairman and Jane Muller was elected vice chairman.

In September 1994, GEARTECH completed NREL Report NREL/TP-442-7076 *Application Requirements for Wind Turbine Gearboxes* [2] prepared under Subcontract No. AAO-3-13247-01. The report documented GEARTECH's experience with wind turbine gearboxes and gave guidelines for selecting, designing, manufacturing, procuring, operating, and maintaining gearboxes for use in wind turbines. The report was accepted by the wind turbine committee as a working draft.

The wind turbine committee met ten times between 1993 and 1996. In 1996, they submitted their draft standard to AGMA for approval. In October of 1997, AGMA published AGMA/AWEA 921-A97 *Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems* [3]. The wind turbine committee set a record for the shortest time from proposal of an AGMA standard to approval and publication.

In 1999, work began on the revision of AGMA/AWEA 921-A97. Because information sheets are less legally binding than standards, the committee decided to upgrade the

document from an AGMA “Information Sheet” to an AGMA “Standard.” They changed the document title to AGMA/AWEA 6006-AXX, *Standard for Design and Specification of Gearboxes for Wind Turbines*. The wind turbine committee met nine times between 1999 and May of 2002 and the document was sent to committee members for comment in December 2002. A meeting to resolve committee comments is scheduled for February 2003. AGMA/AWEA 6006 should be published in 2003.

RECENT GEARBOX FAILURES

Beginning in 1998, widespread failures of gearboxes occurred in wind turbines ranging from 600 kW to 750 kW. This caused one wind turbine company to institute a program to replace gearboxes in over 1200 wind turbines. Many wind turbine companies experienced similar gearbox failures. There were several reasons for the failures, but it became clear that bearing failures were especially prevalent. Bearing manufacturers became concerned about the failures, and the major bearing companies sent representatives to the wind turbine committee. Gearbox failures continue; indicating more research is needed before problems are overcome.

BEARING RATING STUDY

Due to widespread bearing failures in wind turbine gearboxes, the wind turbine committee investigated methods for rating bearing life. With the help of major bearing manufacturers, the committee rated bearings for several examples of actual wind turbine gearboxes. This lead to new guidelines for rating bearing life, and emphasized the need for considering lubricant cleanliness and its effects on fatigue life.

Each bearing manufacturer has an advanced method for rating bearings, and AGMA/AWEA 6006 encourages the use of advanced methods. However, the rating study showed that different life predictions were obtained from each bearing manufacturer. Furthermore, there is insufficient transparency in the advanced methods because they are proprietary. Therefore, the wind turbine committee developed a stress-based analysis that is more easily understood. The significance of internal clearance, misalignment, and effects of microgeometry of rollers and raceways is more readily apparent by calculating stresses rather than fatigue life. The stress-based method is intended to supplement rather than replace advanced methods. It will help auditors evaluate results of advanced methods.

Another result of the bearing study was the realization that lubricant cleanliness has a dramatic effect on bearing life. It became clear that the cleanliness assumed for calculating bearing life was not always achieved in practice. Life predictions decreased by orders of magnitude when life calculations were repeated using actual cleanliness values. Therefore, it is imperative that bearing life calculations be based on reasonable values of cleanliness. Many factors determine oil cleanliness [4].

GEAR RATING STUDY

The wind turbine committee decided to allow gear rating in accordance with ANSI/AGMA 2001 [5] or ISO 6336 [6,7,8,9]. With the help of major gear manufacturers, the committee rated gears for several examples of actual wind turbine gearboxes. The results of the study showed that different life predictions were obtained from ANSI/AGMA 2001 and ISO 6336. This lead to new guidelines for rating gears, and emphasized the need for understanding the differences between ANSI/AGMA 2001 and ISO 6336.

GEARTECH compared ANSI/AGMA 2001 and ISO 6336 gear ratings in several reports to NREL [10,11,12]. The GEARTECH reports show the two standards give different ratings and there is no single factor to convert from an ISO gear rating to an AGMA gear rating. To compensate for the differences, AGMA/AWEA 6006 requires a safety factor of 1.56 for an ISO 6336 rating, whereas the same gearset rated by ANSI/AGMA 2001 should have a safety factor of 1.00.

Purchasers and auditors should understand that ISO 6336 and ANSI/AGMA 2001 give different gear ratings. Therefore, they must decide which standard will be specified in the procurement specification. This decision should be reached through negotiation with the gear manufacturer. AGMA/AWEA 6006 gives specific requirements for applying either ANSI/AGMA 2001 or ISO 6336. These requirements must be followed exactly to obtain accurate gear ratings.

CURRENT WIND TURBINE COMMITTEE

The wind turbine committee started with a handful of people involved in the wind turbine industry. Today it has the same founding members and the same officers. Over time committee membership grew to include a large cross section of people working in the wind turbine industry and supporting industries from the US and Europe. In April of 2001, a long overdue European meeting was held in Randers, Denmark. The response was overwhelming with over sixty people attending. Despite all subsequent meetings being held in the US, foreign participation has remained high.

The quality and scope of the standard has been greatly improved by the worldwide participation of people interested in wind power. The following professions currently participate in the wind turbine committee:

- Purchasers
- Wind turbine manufacturers
- Gear manufacturers
- Bearing manufacturers
- Lubricant manufacturers
- Lubrication component manufacturers
- Consultants
- Monitoring specialists

- Wind turbine operators
- Wind turbine services
- Power industries
- Government agencies
- Certification societies
- Universities
- Private individuals

Representatives from the following countries participate in the wind turbine committee:

- United States
- United Kingdom
- Belgium
- Germany
- Finland
- Denmark
- Japan
- Spain
- Norway
- Switzerland

ACCOMPLISHMENTS OF THE WIND TURBINE COMMITTEE

The wind turbine committee is the largest, and one of the most active AGMA committees. International participation has fostered worldwide acceptance of AGMA/AWEA 6006 guidelines. The Danish Approval Scheme for Wind Turbines has used AGMA/AWEA 6006 as a model for their technical criteria for gearboxes. The interdisciplinary cooperation has lead to important technological advances including:

- Recommended practice for design of all gearbox components
- Recommended procurement procedures
- Recommended quality procedures
- Recommended testing procedures
- New methods for rating gears
- New methods for rating bearings
- Guidelines for tribology
- Guidelines for lubricant cleanliness
- Guidelines for condition monitoring

FUTURE FOR AGMA/AWEA 6006

Publication of AGMA/AWEA 6006 is expected in 2003. AGMA rules require that the document be reviewed by the wind turbine committee within five years from publication, and revised, accepted as is, or withdrawn.

GEARTECH believes committee work should continue. Work by the bearing and lubrication subcommittees has been groundbreaking and the research should continue. It is especially important to keep the standard current with the trend for increasing power capacity of wind turbines. A 250 kW wind turbine was considered large in 1991, but today 1 MW machines are common, and some 3 MW machines are being developed. Gearbox design must change to accommodate higher power wind turbines. GEARTECH believes wind turbine gearboxes will evolve to technology similar to that used by hydropower gearboxes. The following technology is envisioned:

- Epicyclic gears
- Double helical gears
- Hydrodynamic bearings
- Dry sump lubrication with separate reservoir
- Online and offline filtration
- Online monitoring of oil quality
- Online monitoring of gear health
- Online monitoring of bearing health

AN INTERNATIONAL STANDARD

With wind turbines being installed in all parts of the world, it is essential that the standard become an international standard accepted by ISO. Currently, certification societies such as Germanischer Lloyd and Det Norske Veritas audit gearbox designs using their own methods. It is hoped that AGMA/AWEA 6006 becomes the worldwide standard for designing and specifying gearboxes for wind turbines and is adopted by all certification societies.

HOW TO USE AGMA/AWEA 6006

To obtain reliable wind turbine gearboxes, one must know how to use AGMA/AWEA 6006. Obtaining and reading the document is not sufficient; understanding and implementing the specifications requires dedicated resources and careful planning.

Annex D of AGMA/AWEA 6006 is a good starting point for understanding the intent of the standard. It explains the procurement process required to obtain reliable wind turbine gearboxes. It describes the procurement specification, quality assurance plan, quality control tests, quality documentation, and explains responsibilities of purchasers and gear manufacturers.

It is essential that the technical requirements be understood by the purchaser and gear manufacturer. Therefore, the purchaser should begin the procurement process by writing a comprehensive procurement specification that specifies all requirements for the gearbox. The main body of AGMA/AWEA 6006 gives technical requirements that are intended as guidelines for content of the procurement specification. The procurement specification provides a forum for the purchaser and gear manufacturer to negotiate technical specifications until both parties understand the technical

requirements. The gear manufacturer should write a quality assurance plan that is sufficient to achieve the technical requirements of the procurement specification.

Annex F of AGMA/AWEA 6006 explains the information that should be provided by the purchaser to the gear manufacturer, and describes data that gear manufacturers should include in their proposals.

The purchaser must dedicate adequate resources to evaluate gear manufacturer's proposals for conformance to the requirements of the procurement specification. The purchaser should be represented by an independent auditor who has the technical expertise and resources necessary to properly evaluate proposals.

GEARTECH Checklists and Quality Procedures assist auditors in all aspects of gearbox procurement. They provide guidelines for planning gearbox procurement, conducting design audits, and performing manufacturing audits. See GEARTECH Report 2070-1 [13] for more information.

Annex G of AGMA/AWEA 6006 gives comprehensive guidelines for all aspects of tribology for wind turbine gearboxes including lubricant types, additives, filtration, and condition monitoring. The choice of lubricant significantly influences EHL film thickness and fatigue life of gears and bearings [14].

In addition to the technical requirements of the main body of AGMA/AWEA 6006, the annexes give a large amount of useful, practical information. The following is a complete list of the annexes:

Annex	Description
A	Wind turbine architecture
B	Environmental considerations
C	Wind turbine load description
D	Quality assurance
E	Operation and maintenance
F	Minimum purchaser and gear manufacturer ordering data
G	Lubrication selection and condition monitoring
H	General gear information
I	Determination of the application factor K_A from a given load spectrum using the equivalent torque, Teq
J	Bearing stress calculation

REFERENCES

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2. Errichello, R., and Muller, J., "Application Requirements for Wind Turbine Gearboxes", NREL/TP-442-7076, Sept., 1994.
3. AGMA/AWEA 921-A97, “Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems,” 1997.
4. Errichello, R., and Muller, J., “Oil Cleanliness in Wind Turbine Gearboxes”, Machinery Lubrication, Vol. 2, No. 4, July/August 2002, pp. 34-40.
5. ANSI/AGMA 2001-C95, “AMERICAN NATIONAL STANDARD- Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth,” 1995.
6. ISO 6336-1, “Calculation of Load Capacity of Spur and Helical Gears- Part 1: Basic Principles, Introduction and General Influence Factors,” ISO, 1996.
7. ISO 6336-2, “Calculation of Load Capacity of Spur and Helical Gears- Part 2: Calculation of Surface Durability (pitting),” ISO, 1996.
8. ISO 6336-3, “Calculation of Load Capacity of Spur and Helical Gears- Part 3: Calculation of Tooth Bending Strength,” ISO, 1996.
9. ISO 6336-5, “Calculation of Load Capacity of Spur and Helical Gears- Part 5: Strength and Quality of Materials,” ISO, 1996.
10. GEARTECH Report No. 1974, “Comparison of ISO 6336 and AGMA 2001 Load Capacity Ratings for Wind Turbine Gears,” Prepared for NREL under subcontract No. EXL-8-17497-01, Dec., 2000, pp. 1-14.
11. GEARTECH Report No. 1992, “Comparison of ISO 6336 and AGMA 2001 Load Capacity Ratings for Wind Turbine Gears- Sensitivity Study for Profile Shift, Helix Angle, and Normal Pressure Angle,” Prepared for NREL under subcontract No. EXL-8-17497-01, Jan. 3, 2002, pp. 1-11.
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13. GEARTECH Report No. 2070-1, “Guidelines for Wind Turbine Gearboxes,” Prepared for NREL under subcontract No. EXL-8-17497-01, Dec. 31, 2002, pp. 1-10.
14. GEARTECH Report No. 2038, “Comparison of EHL Film Thickness versus Temperature Characteristics of Mineral, PAO, and PAG Lubricants,” Prepared for NREL under subcontract No. EXL-8-17497-01, May 31, 2002, pp. 1-9.